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Wide-area Differential Global Positioning System (WDGPS)/Wide-area Integrity Broadcast (WIB) Alternatives Analysis

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Final Report

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ABSTRACT

A study was conducted by MITRE to determine alternative concepts for Wide-area Differential Global Positioning System (WDGPS) for the national airspace system (NAS). The study was undertaken in support of the concept exploration phase analyses required by the Transportation System Acquisition Review Council (TSARC). The results of the study are documented in this paper. The paper provides a description of alternatives to WDGPS, various alternative implementations of WDGPS, advantages and disadvantages of each alternative, and risk areas which were identified. Two WDGPS architecture end-states are recommended. The preferred end-state will depend on the results of required trade-off studies which are identified in this paper. A plan for the transition from the Wide-area Integrity Broadcast (WIB) to the selected WDGPS end-state architecture is also presented.

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SECTION 1

INTRODUCTION

1.1 PURPOSE

The purpose of this report is to document an analysis that was undertaken by MITRE in support of the acquisition by the Federal Aviation Administration (FAA) of Wide-area Differential GPS (WDGPS) and Wide-area Integrity Broadcast (WIB). The objective of the analysis was to investigate reasonable alternative approaches or concepts to WDGPS/WIB to determine if they would meet the mission need and to evaluate the alternative concepts in terms of performance, cost, schedule, institutional issues, and risk. The study was undertaken in support of the concept exploration phase analyses required by the Transportation System Acquisition Review Council (TSARC).

It is assumed that the reader of this report is familiar with WDGPS [1] and WIB [2] concepts.

1.2 SCOPE

The mission needs were derived from an FAA memorandum concerning a request for mission need approval [3]. The first mission need *identified in this memorandum* was the need to provide sole means navigation capability for all phases of flight in the National Airspace System (NAS) from en-route through non precision approach. The second mission need that was identified was the need to provide near Category I (CAT I) precision approach service to a large number of runways in the NAS. This will potentially extend precision approach service to runways and airports that currently do not have the Instrument Landing System (ILS). In this study, we focused on the second mission need, to provide near CAT I service to a large number of runways. Near CAT I performance requirements are more stringent than those of any other phase of flight between en-route and non precision approach. The role that WDGPS will have in the future precision approach system architecture is being addressed by the joint FAA/Department of Defense (DoD) NAS Precision Approach and Landing System (NASPALS) effort [4].

The alternatives to WDGPS/WIB that were considered in this study were limited to satellite based navigation systems. These included existing long-range DGPS services and undiluted GPS. There were no limitations placed on alternative implementations of WDGPS/WIB.

The different alternative approaches and concepts were evaluated in terms of performance (accuracy, availability, and integrity), institutional issues, operational suitability, and FAA and user costs. Risk areas associated with any alternative were also identified.

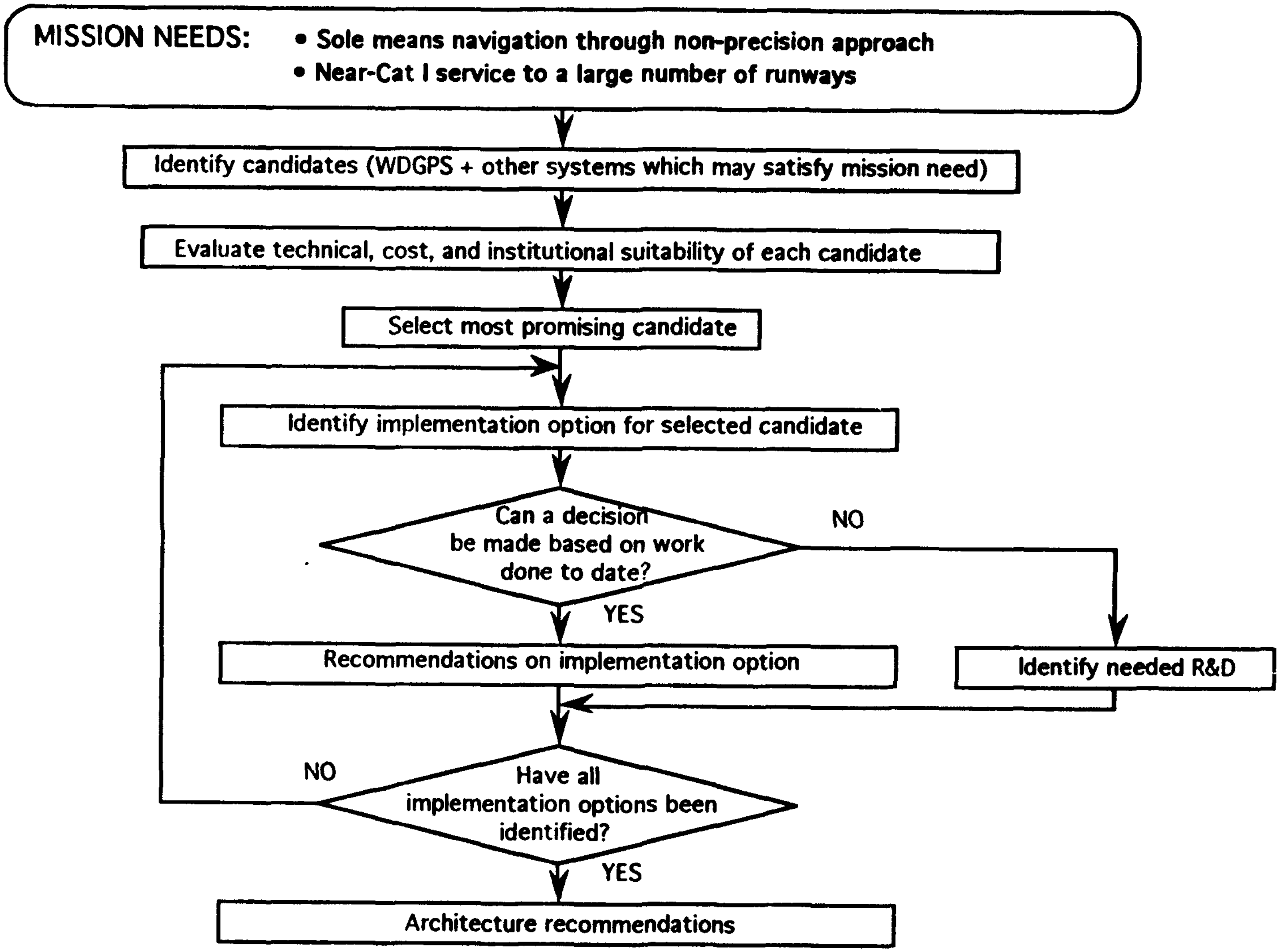

Figure 1-1. Decision Process

1.3 APPROACH

The decision process that was followed for the alternatives analysis is depicted in figure 1-1. Essentially this process was two-fold. First, the alternative system concepts which might satisfy the mission needs were identified, evaluated and compared to verify that WDGPS is indeed the most promising concept. Second, the various implementation options of WDGPS were identified. Each of these options represents a decision which must be made if WDGPS is to be implemented. Recommendations on each option were made whenever it was felt that sufficient work has been done to date to support a decision. When there was insufficient data to support a recommendation, additional research and development activities were identified. Finally, all the implementation option recommendations which were made are used to produce a set of recommendations on the overall architecture.

1.4 REPORT ORGANIZATION

Section 2 of this report describes the assumptions that were used in this study. Section 3 contains the analysis of alternative system concepts. In this section the various system concepts are described and compared, and the recommendation of WDGPS/WIB is made. Section 4 analyzes various implementation options of WDGPS/WIB and either makes recommendations on each option or identifies the research and development that is needed before an informed decision can be made. Section 5 presents architecture recommendations. Section 6 provides a summary of the recommendations and section 7 identifies the risk issues that were identified for the various stages of WDGPS implementation.

SECTION 2

ASSUMPTIONS

This section describes the assumptions used in this analysis. First, assumptions concerning the navigation performance required for a near CAT I approach are presented. Following this, reasons are presented for disregarding certain alternative concepts that have been proposed for near CAT I precision approaches. These alternative system concepts include the use of Global Navigation Satellite System (GLONASS), and the use of GPS with Receiver Autonomous Integrity Monitor (RAIM). Finally, the assumption of using planned WIB monitor stations as the basis for the WDGPS system is presented.

2.1 NEAR CAT I PERFORMANCE

The requirements for near CAT I have not been defined. Ranges for the accuracy, integrity, and availability requirements* for WDGPS/WIB have been proposed by Loh [5]. These values are as follows:

Accuracy

- Vertical sensor error: 4.1 - 9.4 m
- Vertical total system error: 9.7 - 11.6 m

Integrity

- Time to alarm: 6 - 10 s
- Maximum alarm rate: 0.002 per hour (17.5 alarms per year)
- Detection probability: 0.999 (1 undetected failure in 57 years) to 0.9999 (1 undetected failure in 570 years)

Availability

- Availability: 0.99999 (5.3 minutes unavailability per year)
- Reliability/Continuity of service: 0.999992

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* Accuracy refers to the ability of a navigation system to estimate position and/or velocity without error. Integrity refers to the ability of a navigation system to provide timely warnings to users when the system should not be used for navigation. Availability refers to the percentage of time that the services of a system are usable.

The availability requirement is currently under review and recommendations may be made for a new way to specify this requirement. In addition, requirements are now being developed for lateral sensor error performance. The lateral requirements are less stringent than those for vertical sensor error and will likely be satisfied once the vertical requirements are met.

2.2 ALTERNATIVE CONCEPTS WHICH WERE DISREGARDED

The analysis disregarded certain alternative concepts. For example, an alternative system concept consisting only of the Russian navigation satellite system, GLONASS, was disregarded because of the high risk associated with this choice. The high level of risk is due to the following factors : 1) there is uncertainty when GLONASS will become fully operational because of political, technical, and other problems, 2) there are problems with the GLONASS satellites' reliability (maximum satellite life has been 3 years), and 3) there is a potential radio frequency interference problem (the World Administrative Radio Conference (WARC) '92 has allocated portions of the GLONASS spectrum to communications satellites and radio astronomy.) However, the possibility of using GLONASS, when it becomes available, along with other systems to enhance availability was not disregarded. If GLONASS is used, it should be used with wide-area differential corrections.

An alternative concept consisting of only GPS with RAIM was also not considered. The combination of GPS and RAIM will not achieve the vertical accuracy or the availability required for near CAT I. Accuracy is not improved by RAIM and availability with RAIM is reduced because of the requirement for at least 5 space vehicles (SVs) to be in view of the user equipment for supplemental navigation and at least 6 SVs for sole-means navigation. However, it is assumed that all GPS receivers in the system concepts considered in this paper may include RAIM as part of an integrity check.

2.3 USE OF WIB MONITOR STATIONS

In this study, the assumption was made that the planned WIB will be implemented, and can be used as a foundation upon which the WDGPS system can be built. WIB would consist of a network of integrity monitoring stations located throughout the country. Its purpose would be to monitor the integrity of the GPS signal for all phases of flight from en-route through non precision approach. The types of equipment required at both WIB monitor stations and WDGPS reference stations are roughly equivalent.

SECTION 3

ALTERNATIVE SYSTEM CONCEPTS

This section describes three alternative system concepts for providing sole-means navigation and guidance for near CAT I precision approaches at a large number of runways. This set represent the range of alternatives that could potentially meet the mission needs. The concepts include WDGPS/WIB, existing long-range differential GPS (DGPS) services [6,7], and undiluted GPS. After describing these three alternatives, this section provides a comparison of the three, and based on the comparison recommends the WDGPS/WIB system concept.

3.1 WDGPS/WIB

For the WDGPS system concept, the FAA would implement a network of Wide-area Reference stations (WRSs). The WRSs would make measurements of GPS signals and local weather (for tropospheric corrections), and communicate these measurements to two or more Wide-area Master Stations (WMSs). The WMSs would use these measurements to estimate the error components for each satellite. The corrections would be broadcast to users and would be applicable over a wide area.

3.2 EXISTING LONG-RANGE DGPS SERVICES

The second alternative concept is to use existing long range Local Area Differential GPS (LADGPS) services. Examples are Pinpoint and SkyFix. The concept consists of a network of many LADGPS stations that would individually estimate GPS pseudorange corrections. A user passing through the area of coverage of a LADGPS station would apply the pseudorange corrections to their solution. These services typically have limited coverage across the conterminous United States (CONUS), and for near CAT I operations the corrections are applicable only near each LADGPS station.

3.3 UNDILUTED GPS

The third concept is an undiluted form of GPS. In this concept, no ground network of WRSs would be required. Instead, the guaranteed use of P-code, no Selective Availability (SA), and a means of insuring integrity would be assumed. However, it should be noted that the DoD has shown no intention to change its policy about P-code availability or SA, and that this alternative is included only for completeness sake.

3.4 COMPARISON

Table 3-1 provides a comparison of the three alternative concepts. Concerning the summary in the far right column, WDGPS has the best performance potential of the three methods. Its accuracy and integrity performance is expected to be adequate through near CAT I precision approaches. The drawback of WDGPS is that it is a relatively new system concept so there is no operational experience with it.

The concept of using existing long range DGPS services such as Pinpoint and SkyFix have major drawbacks for the near CAT I application in that they have limited coverage over CONUS, for both the applicability and the broadcast of the correction. The applicability of the correction is only adequate when the user is near the reference station providing the corrections [8], at most about 200 nmi. These systems are typically used for ground based applications (e.g., trucking, and off-shore oil drilling), hence there is no operational experience by these providers with airborne applications, vertical performance, and integrity monitoring concepts. Institutionally, these services are privately operated and the FAA would have limited control. This may have an impact on the ability of the FAA to guarantee a certain level of service to users of these systems. In addition, private operators charge a direct user fee which is counter to FAA policy of no direct user charges. Finally, Pinpoint, which uses FM radio broadcast to provide the differential corrections, may have an interference problem for users at high altitudes where the broadcasts from two stations are in line-of-sight view.

Option 3, Undiluted GPS assumes P-code availability and no SA. However, the current Department of Defense (DoD) policy is that the P-code would not always be made available and SA may be applied at any time. This is the major drawback of this system option. However, even with guaranteed P-code availability and no SA, this method would not have the vertical accuracy, or integrity required for a near CAT I precision approach without some augmentation.

Achieving adequate availability may be a problem for all three options, and some form of augmentation, either with other sensors, more geostationary transponders, or more GPS SVs, may be required. These augmentations will be described later in this report.

3.5 RECOMMENDATION

The concept recommended is WDGPS. Performance adequate for a near CAT I precision approach is achievable (with augmentation if required for availability). Existing long range DGPS services or undiluted GPS are not recommended.

Existing long range DGPS services provide the required horizontal performance only when the user is near the reference station. To provide the necessary coverage over CONUS, these systems would have to be enhanced with many more WRSs, vertical performance guarantees,

Table 3-1. Alternative Concepts Comparison

SYSTEM OPTION	TECHNICAL PERFORMANCE	INSTITUTIONAL	COST		SUMMARY COMPARISON	
			FAA	USER	+	-
WDGPS/WIB (Option 1)	Accuracy and integrity expected to be adequate. GPS SV availability may be questionable, thus system may require some form of augmentation.	FAA would have control over differential system..	Ground stations plus lease of geostationary transponders.	Would require GPS receiver slightly modified to process differential corrections	Performance potential FAA control	No operational experience Questionable availability
Existing Long Range LADGPS Services (Option 2)	Accuracy adequate only *if user* within certain range of reference stations. Most systems have limited coverage (in terms of accuracy, applicability of correction, and broadcast). Integrity may not be adequate.	Systems are independently owned and operated, limiting FAA control over system (e.g. integrity).	Lease of service	In addition to GPS receiver, this approach *would* require separate avionics to receive differential corrections.	Earlier GPS differential service	Limited coverage for advertised accuracy No operational experience with airborne systems Lack of FAA control Pinpoint [5] may have interference problem at high altitudes.
Undiluted GPS (Option 3)	Possibly adequate assuming augmentation for integrity, vertical accuracy, and availability.	DoD controls use of SA and encryption of P-Code.		Would require only GPS receiver.	No ground infrastructure needed	DoD policy on P-Code availability and SA Cost of additional SVs, other augmentations to achieve performance

and integrity monitoring capabilities. In addition, because of limited FAA control over the system it is unclear how the FAA would guarantee users a certain level of service.

Undiluted GPS was not recommended for two reasons: 1) the DoD policy on P-code availability and SA, and 2) the system, even with guaranteed P-code and no SA, would not be able to achieve the accuracy or integrity required for a near CAT I precision approach without major augmentations. This concept was considered for completeness only.

SECTION 4

WDGPS IMPLEMENTATION ALTERNATIVES

This section presents several WDGPS implementation alternatives. The alternatives addressed in this study included choice of broadcast media, correction technique, reference station facility sharing, network interconnections and augmentations. Besides describing the various options for each of these areas, this section discusses the advantages and disadvantages of each option, and when appropriate makes a recommendation.

4.1 OVERVIEW

The functional areas in which several options exist for WDGPS include:

- Broadcast media - The corrections generated by the ground network need to be broadcast to the user through some communications link.

- Correction technique - This area includes type of corrections generated by the ground network and how they are employed by the user.

- Reference station facility sharing - Several options exist for siting the reference stations including the possibility of sharing FAA and United States Coast Guard (USCG) reference stations.

- Network interconnections - There are a variety of communications links which may be used to connect together the elements of the ground network.

- Augmentations - Augmentations may be necessary to achieve the desired level of availability.

The criteria for which the options are evaluated include technical performance, operational suitability, institutional acceptability and both FAA and user costs.

4.2 BROADCAST MEDIA

The following broadcast media options for both WDGPS and WIB were investigated:

- Geostationary ranging signal - The WDGPS/WIB data can be used to modulate a GPS-like ranging signal on L1 broadcast from a geostationary satellite. The broadcast signal would require only minor software changes to existing user equipment designs and would provide a data rate of around 250 bits/second.

Additionally, the ranging signal increases GPS availability. The cost of leasing a navigation package on one of Inmarsat's latest generation of satellites which is capable of providing such a signal would cost approximately $2.2 M per year according to a COMSAT estimate [9]. A similar navigation package could be placed on other planned geostationary satellites including the DoD's Defense System Communication Satellites (DSCS).

- Narrowband geostationary satellite broadcast - This option consists of a generic geostationary satellite link. High data rates may be attained since the signal is not restricted to the GPS format, but an additional receiver or highly modified GPS receiver would be required to receive the signal. The cost of service might be somewhat less than option 1 since existing satellite ground/air services may be used and no special navigation package would be required.

- VHF/UHF - The FAA controls a large number of Very High Frequency (VHF) and Ultra High Frequency (UHF) transmitters across CONUS. These transmitters could be used to transmit the WDGPS/WIB corrections on dedicated navigation frequencies, but several technical difficulties would need to be overcome. The transmitters operate over line-of-sight (LOS), so a large number would be needed and still, coverage would be limited. Each of these would need to receive WDGPS/WIB corrections from the WMSs in real-time, placing a large burden on the communication links used as network interconnections*. Also, digital modulation equipment would need to be installed on the ground and in the airborne systems, dedicated channels obtained, and integrity monitoring stations installed.

- Mode-S - En-route Mode-S radars rotate on the order of once every 12 seconds and this is the minimum data delay unless a back to back antenna is employed. The 12 second delay exceeds the required 6-10 second integrity warning time, and for this reason use of the traditional Mode-S data link does not appear feasible for WDGPS. However, an omnidirectional Mode-S broadcast has been proposed by Lincoln Labs which could meet the integrity delay requirements. Mode-S is LOS and thus would have the same problems as detailed for media option 3*. The general aviation (GA) community also may have objections to the expense of the airborne Mode-S equipment. This option would have the same problem as VHF/UHF with regards to distributing corrections from the WMSs to the transmitter sites. Since the Mode-S frequency is not protected for navigation, there is also a chance for interference at a busy airport.

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* Alternatively, it would be possible to have a reference station collocated with each transmitter. However, this scenario would require an unmanageable number of reference stations and still coverage would be limited due to the LOS characteristic of this broadcast media.

- Nondirectional Beacon (NDB) - The FAA operates over 700 aeronautical NDBs to provide a transition from en route to precision terminal approach facilities and as nonprecision approach aids. It is possible to modify the beacons to broadcast differential GPS corrections (the USCG has done this with certain marine radiobeacons). However, the data rate that could be accommodated would most likely be inadequate to provide near-CAT I accuracies (the USCG radiobeacon broadcasts are at 50 bits/second). Additionally, the NDBs have limited coverage over CONUS (each NDB covers at most a few hundred miles over ground and typically much less). This option would have the same problem as VHF/UHF with regards to distributing corrections from the WMSs to the transmitter sites* .

- VHF Omnidirectional Range (VOR) - The FAA operates 950 VOR transmitters to provide bearing information to aircraft. These transmitters could be modified to broadcast differential GPS corrections. However, these transmitters have incomplete low altitude coverage over CONUS, and also this option would have the same problem as VHF/UHF with regards to distributing corrections from the WMSs to the transmitter sites*.

Table 4-1 provides a comparison of the six media options. Based on this comparison the geostationary ranging signal concept for broadcasting WDGPS corrections is the recommended broadcast media option. This concept provides a reliable data link at minimum cost to the user with the additional benefit of also increasing GPS availability by providing additional ranging signals. Inmarsat's third generation of satellites (Inmarsat-3) is the most likely candidate for initial service. These satellites are scheduled to be launched in the 1994-1995 time frame and will carry a navigation package capable of broadcasting WDGPS corrections.

The Inmarsat-3 satellites alone will not be sufficient to provide WDGPS service over all of CONUS with adequate redundancy, however. A single satellite failure could disrupt service over a large portion of the mid-west until redundant Inmarsat satellites are launched sometime around the year 2000. Other satellites which will be launched sooner than this and are capable of carrying a similar payload should be investigated (e.g. DSCS).

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* Alternatively, it would be possible to have a reference station collocated with each transmitter. However, this scenario would require an unmanageable number of reference stations and still coverage would be limited due to the LOS characteristic of this broadcast media.

Table 4-1. Comparison of Broadcast Media Options

MEDIA	TECHNICAL PERFORMANCE	INSTITUTIONAL	COST FAA	COST USER	SUMMARY COMPARISON +	SUMMARY COMPARISON -
Data modulated on geostationary ranging signal on GPS L1 band (Option 1)	Data rate, integrity, error rate, etc. thought to be adequate GPS availability enhanced by ranging signal	SV transponders may be privately owned (Inmarsat, etc.) or gov't owned (e.g. DSCS)	$2.2 M per SV per year for Inmarsat service (COMSAT estimate) Transponder package for gov't owned SV	Minor modification to GPS receiver design	Only minor modification to GPS receiver design required Ranging signal aids GPS availability	Cost of leasing SV L1 transponder service
Narrowband geostationary broadcast (Option 2)	High data rate	SV transponders privately owned	Transponder service must be leased	Requires addtn'l rcvr or modification to GPS rcvr front-end	High data rate Can use existing satellites	Addtn'l or modified rcvr required by user Cost of leasing SV transponder service Frequency allocation
VHF/UHF (Option 3)	High data rate but technical limitations: - LOS coverage - Large number of transmitters must be connected to WMS or operated as LADGPS - Channel allocation . - May lose independence of nav. and ATC comm.	FAA owns transmitters	Broadcast facilities would need digital modulation equipment Communication links to WMSs may be needed	VHF/UHF receiver and interface required	Provides high data rates	Line of sight: - limited coverage - many monitors Cost of digital modulation equipment New channels might be hard to obtain
Mode-S (Option 4)	- Data rate sufficient assuming omnidirectional broadcast - Large number of transmitters must be connected to WMS or operated as LADGPS - Coverage gaps below 12,000 ft - May lose independence of nav. and ATC comm.	FAA owns ground equipment	Additional transmitters would be needed	Mode-S equipment required	Opportunity to piggyback on a planned service	Line of sight: - limited coverage - many monitors Bandwidth congested, potential interference problem s Cost of Mode-S avionics for GA
NDBs (Option 5)	- Insufficient data rate - Many transmitters - Coverage limitations	FAA owns transmitters	Beacons would require digital modulation equipment	Automatic Direction Finder and data link interface required	Opportunity to piggyback on an existing service	Limited coverage Insufficient data rate
VOR (Option 6)	- Coverage limitations - Many transmitters	FAA owns transmitters	VOR transmitters would require digital modulators	VOR receiver and data link interface required	Opportunity to piggyback on an existing service	Limited coverage

4.3 CORRECTION TECHNIQUE

The following correction techniques were identified as candidates:

- Precise zonal - This technique [10] consists of sending the user pseudorange corrections only. The pseudorange corrections are separated into "fast" and "slow" components. The fast components are primarily clock corrections (including SA) and are updated at a frequent rate. The slow corrections are issued for each of a set of zones (geographic regions) and consist of a composite of coarse clock, ephemeris and ionospheric delay. The slow corrections may be updated at a somewhat lesser rate as the errors that they correct do not change very rapidly over time. The main advantage of the precise zonal concept is that single-frequency receivers could be used at the reference stations. Disadvantages include errors that are introduced through the necessary interpolation between zones, and also the ionospheric delay portion of the correction cannot be isolated, thus negating any possible benefit from dual-frequency user equipment. Dual-frequency equipment is expected to be capable of producing its own accurate ionospheric delay estimates.

- Fully separated (clock, ephemeris and ionospheric) - In this technique, the clock, ephemeris and ionospheric delay components of the ranging errors are broadcast to the user. The only interpolation needed in the user equipment is for the ionospheric delay values which are issued as a function of location. The clock and ephemeris corrections are applicable anywhere. In addition, users equipped with dual-frequency (either P/Y code or codeless) receivers can directly measure ionospheric errors and use only the clock and ephemeris corrections provided by the ground network. The cost of the WDGPS ground network is marginally increased since dual-frequency receivers are needed at the reference stations.

- Fully separated (clock and ephemeris only) - By requiring that the minimum user equipment be capable of providing its own ionospheric delay measurements, e.g. dual-frequency), the ionospheric portion of the message can be eliminated [11]. The saved bandwidth can be used to transmit the clock corrections more rapidly to allow slightly higher accuracies. Roughly half the number of reference stations are needed by this technique as compared to the other techniques, since the ground network is not responsible for providing the user ionospheric data.

A comparison of the correction techniques is shown in table 4-2. Either of the fully separated techniques (options 2 and 3) is recommended since they provide the highest accuracy for users with airborne ionospheric measuring equipment. Option 3 also provides the minimum ground network cost; however, it is realized that the GA community may have objections to the requirement for the more expensive dual-frequency equipment. In addition, the performance of codeless dual-frequency airborne ionospheric estimation techniques needs

Table 4-2. Comparison of Alternative WDGPS Correction Techniques

CORRECTION TYPE	TECHNICAL PERFORMANCE	COST		SUMMARY COMPARISON	
		FAA	USER	+	-
Precise zonal pseudoranges (fast/slow corrections as proposed by RTCA) (Option 1)	Probably adequate if data is collected for enough zones (≈20 for CONUS)	≈20 single-frequency reference stations Additional local integrity monitors will be required		Easily implemented Single-frequency receivers can be used at reference stations	Errors are introduced through necessary interpolation Dual-frequency receiver advantage is lost since ionospheric portion of pseudorange error is inseparable Accuracy degrades rapidly outside of reference station coverage area
Fully separated clock, ephemeris and ionospheric corrections (Option 2)	High accuracy	≈20 dual-frequency reference stations	Ionospheric measuring equipment (e.g. dual-frequency rcvr) optional for lower decision heights	Separate ionosphere allows dual-frequency users to use their own delay estimates	Highest data rate Complex processing is required by ground equipment to separate clock and ephemeris errors Complex processing is required by ground equipment to generate ionospheric error components
Fully separated clock and ephemeris without ionospheric corrections (airborne ionospheric measurement) (Option 3)	Highest accuracy assuming user can measure ionosphere	≈10 dual-frequency reference stations	Ionospheric measuring equipment required (e.g. dual-frequency rcvr w/codeless L2)	Number of required reference stations is reduced Allows more rapid clock updates since most or all ionospheric data is eliminated	Complex processing is required by ground equipment to separate clock and ephemeris errors Requires that users have equipment to measure the ionosphere (e.g. dual-frequency rcvr w/codeless L2)

further investigation. If the cost or technical performance issues cannot be resolved, option 2 may be the more favorable choice. Option 2 could allow all users near-CAT I accuracies with lower decision heights for users with the potentially more accurate ionospheric delay provided by airborne receiver measurements.

The processing algorithms used to separate the pseudorange error components have a significant impact on the accuracy and integrity of the WDGPS system and continue to be investigated [12].

4.4 REFERENCE STATION FACILITY SHARING

Table 4-3 provides a summary comparison between various options of shared use of WRSs for both WIB and WDGPS. The general idea is that since the USCG is implementing a number of LADGPS facilities to provide differential corrections to marine users along coastal waterways, the FAA should consider their use for the WDGPS system. The table looks at three options that were considered in this study: 1) use USCG reference stations only, 2) use FAA WRSs located at FAA facilities, and 3) use a hybrid of both USCG and FAA stations.

Initially there appears to be considerable cost savings by using USCG reference stations, however, this study found that any potential facility sharing cost savings may be offset by the cost of the communication link required to get the measurements to the WMS for processing. This is potentially a major drawback of using USCG reference stations. In addition, since USCG stations are LADGPS stations and use only single-frequency GPS receivers, they would have to be equipped or upgraded with dual-frequency receivers so that the ionospheric delay could be estimated if option 2 or 3 of the alternative correction techniques were employed. In addition, the integrity monitoring concepts may have to be modified for aviation use (e.g., 6 second alarm time).

The use of FAA WRSs located at FAA facilities would be advantageous because they would provide good overall coverage across CONUS, they would be located near maintenance staff, and the cost of connecting them with the WMS would be minimal since the interfacility communications infrastructure at FAA facilities is already in place.

A hybrid approach of USCG and FAA WRSs was also studied. In this approach, a few USCG reference stations along the two coasts would be used together with FAA WRSs located in the interior. Like the first option, this approach is also potentially more costly than using only FAA WRSs because of the cost of the communication links for the USCG reference stations.

The reference station recommendation is to implement WIB/WDGPS WRSs located principally at FAA Air Route Traffic Control Centers (ARTCCs) or other type of major FAA facility.

Table 4-3. Reference Station Facility Sharing

OPTION	TECHNICAL PERFORMANCE	OPERATIONAL SUITABILITY	INSTITUTIONAL	FAA COST	SUMMARY COMPARISON +	SUMMARY COMPARISON -
Use planned USCG reference stations (Option 1)	Good coverage around coastal waterways, poor inland coverage	Stations may be at unmanned locations	USCG would operate and maintain.	Upgrade of reference station to measure iono delay (need dual frequency receivers), tropo delay Comm. link to connect USCG station with WMS.		FAA cost to equip/upgrade USCG reference stations and add comm. links likely to offset any facility sharing cost savings.* Availability impact with unmanned maintenance Limited FAA control over system Poor inland coverage
Use FAA WRSs at FAA facilities (e.g. at ARTCCs) (Option 2)	Good overall coverage	Stations would be near maintenance staff	FAA would operate and maintain	Cost of complete WRSs.	Good overall coverage WRSs operated by FAA	
Use hybrid of USCG and FAA WRSs (Option 3)	Good overall coverage	Some stations would be located near maintenance staff	FAA would operate WRSs at FAA facilities, USCG would operate USCG reference stations	Cost of complete WRSs at FAA ARTCCs (but fewer would be required than option above) Cost of upgrading USCG stations	Good overall coverage FAA operates subset of WRSs Partially integrate air/marine DGPS	FAA cost to equip/upgrade USCG reference stations and add comm. links likely to offset any facility sharing cost savings.* Unstaffed maintenance at USCG reference stations. Complexity with joint operated system

* See interfacility communications alternatives

There did not appear to be a net benefit to shared use of USCG stations. The study found that the potential facility sharing cost savings would be offset by the additional communications links that would be required between the USCG reference stations and the WMS.

4.5 NETWORK INTERCONNECTIONS

The network interconnections which were considered are:

- Existing or planned FAA communications [13] - If the reference stations are located at FAA facilities, the highly reliable communication infrastructure connecting these facilities may be utilized. This infrastructure includes or soon will include:

    - Leased Interfacility NAS Communications System (LINCS) - a highly redundant network of leased lines

    - Radio Communications Link (RCL) - a FAA microwave radio backbone

    - FAA Telecommunications Satellite (FAATSAT) - point to point satellite circuits

    - Routing and Circuit Restoral (RCR) - a program to provide switching and multiplexing systems to interconnect all of the above

- Non-FAA leased phone lines - If the reference stations are not at FAA facilities, leased phone lines may be used to connect the WRSs to the WMSs. However, the reliability of public telephone networks would most likely be inadequate. Adequate reliability can only be attained if the lines are fully redundant along the entire transmission distance. Such redundancy is very expensive to obtain over long distances.

- VSATs - Very Small Aperture Terminals (VSATs) could provide a reliable network between the WRSs and WMSs as well as between the WMSs and broadcast facilities. The terminals are small, inexpensive and can be placed almost anywhere in CONUS (coverage region of Hughes and Contel services), although an expensive hub must either be purchased or leased. K band VSATs may fade during heavy rain [14] and thus should be avoided or used only with diversity techniques or a backup (such as leased lines).

- Other satellite links - Various other satellite communications services exist for both domestic and international connections. Many may provide the needed level of availability. The cost of these services varies greatly depending on the distance of the desired connection.

If the WRSs are located at FAA facilities (e.g. ARTCCs), the obvious choice is to take advantage of the existing (or planned) FAA interfacility communication networks (see table 4-4 for comparison). These networks have been designed to provide high reliability and availability, and should be able to easily handle the small flow of data required for a WDGPS ground network. Indeed, the availability of such a reliable communication infrastructure should be a driving factor in locating the WRSs at FAA facilities.

If the WRSs are not located at FAA facilities, VSATs backed up by leased lines may be the least expensive option, although substantially higher than the first option, and should provide the needed level of reliability. If reference stations in other countries are used, there are a number of satellite services which could provide adequately reliable service.

4.6 AUGMENTATIONS

An availability analysis needs to be completed to validate the 0.99999 availability requirement [15] and to determine if some form of augmentation is required for WDGPS navigation. Table 4-5 provides the comparisons made between various types of sensor augmentations, including: 1) barometric or radio altimeter, 2) atomic clock coasting, 3) inertial sensors, and 4) additional SVs (e.g., civil-type GPS, DSCS, or Inmarsat satellites). The advantages and disadvantages of each option will be briefly discussed.

The barometric altimeter augmentation to GPS may be able to address the availability concern. The technical standard order TSO C129 gives one implementation for augmenting the RAIM algorithm with pressure altitude from the barometric altimeter. In this implementation, the pressure altitude information output from the altimeter would be corrected/calibrated in flight using GPS derived altitude when and only when the maximum subset Vertical Dilution of Precision (VDOP) is less than or equal to 5 and a test statistic is below threshold [16]. This implementation should be studied to determine if this augmentation is appropriate for the precision approach phase of flight and, if so, to determine if the availability is increased sufficiently to satisfy near CAT I availability requirements. If the augmentation is used during the precision approach phase of flight, the performance of the altimeter needs to be assessed for rapidly changing weather, temperature effects, and the effect of the distance between the airborne sensor and the local pressure sensor. The operational suitability needs to be assessed to determine whether the local pressure updates should be updated manually or automatically, and if automatic, to define the data link and airborne interfaces that would be required.

The clock coasting augmentation may be able to address the availability concern. Better clocks with greater stability would also improve availability but at an increased cost to the user. (There have been recent developments in the area of low cost Cesium clocks with good

Table 4-4. Interfacility Communication Options

COMM LINK	TECHNICAL PERFORMANCE	INSTITUTIONAL	COST	SUMMARY COMPARISON +	SUMMARY COMPARISON -
Existing or planned FAA inter-facility comm-unications(LINCS, RCL, etc.) (Option 1)	Probably adequate	FAA networks (some equipment is leased)	Lowest cost due to existing infrastructure	High reliability and availability Already existing or planned	Some networks (e.g. LINCS) are not fully operational yet Only connects FAA facilities
Non-FAA leased phone lines (Option 2)	Probably adequate if fully redundant	Lines are privately owned	Very expensive to obtain full redundancy	Can be used to connect reference stations not located at FAA facilities	Full redundancy is very expensive to obtain Full spatial diversity is very difficult to obtain
VSATs (Option 3)	K-band VSATs may fade during rain	SVs are privately owned (e.g. Hughes or Contel for domestic service)	May be less expensive than fully redundant non-FAA leased phone lines	Can provide redundant routing from anywhere in CONUS	Heavy rain may disrupt service if K-band is used
Other satellite links (Option 4)	Probably adequate	SVs are privately owned	Depends on service provider and distance of desired connection	Alternative for international or long-distance domestic links	Cost effective only for long-distance links

TABLE 4-5. Augmentation Options for Availability (Sole Means Navigation)

OPTIONS	TECHNICAL PERFORMANCE	OPERATIONAL SUITABILITY	INSTITUTIONAL	COST		SUMMARY COMPARISON	
				FAA	USER	+	-
Baro or Radio Altimeter (Option 1)	Would address availability concern, if performance can be shown to be adequate for vertical guidance	How local barometric pressure would be entered into system (manual or automatic via data link) Radar altimeter would require terrain map database for airports or allowed use only at selective locations	Radar: Maintain and update terrain map	Baro: Cost of data link for automatic updates of local pressure Radar: Cost of developing terrain database, and tracking changes	Baro: Minor modifications to GPS receiver Radar: Cost of radar altimeter if not already there, and additional processing in GPS receiver Both: Cost of data link	Increased availability Improved vertical accuracy	Operational suitability Cost of radar altimeter No independent source to determine decision height
Clock Coasting (Option 2)	Might address availability concern, performance of technique unknown	No change		None	Cost of additional capability in GPS receiver	Low FAA cost Possibly improved availability	Unknown performance
Inertial (e.g. IRS) (Option 3)	Inadequate accuracy to address availability concern, may improve continuity of service.	No change		None	Minor modifications to GPS receiver Major cost for INS for general aviation community	Low FAA cost Increased continuity of service	Unresolved availability concern Cost for general aviation community
Additional SVs (Geostationary transponders or civil type GPS) (Option 4)	May require many (~6) geostationary transponders May require many (>10) additional SVs to address availability concerns	Leased transponders	Geostationary transponders would be leased FAA or DoD would operate and maintain additional GPS SVs	About $2.2M per year for each transponder About $43M for each FAA provided SV	None	Increased availability	FAA cost

stability). If only short term clock coasting can be achieved then continuity of service may be improved, but not the availability.

The inertial sensor augmentation does not have the accuracy required to address the availability concern. Typical Inertial Reference Systems (IRSs) have a long term vertical error rate that would, even after a few tens of seconds without update, cause the system to exceed the requirements for a near CAT I precision approach. However, it would address the continuity of service for short term outages. Another disadvantage of this augmentation is its cost to the GA community.

Additional SVs tailored to civil requirements would address the availability concern but at the additional cost of approximately $43M for each FAA provided SV [17]. This figure includes reduced launch costs, with the assumption that two civil GPS-like SVs could be launched simultaneously using one launch vehicle. Other options include using a transponder service on Inmarsat 3 satellites or DSCS satellites to broadcast a GPS like signal to users. Preliminary studies have shown that 6 transponders on geostationary satellites may achieve the required level of availability.

A study needs to be performed to develop/validate the availability requirement for near CAT I operations, especially at new qualifying facilities and to determine if the WDGPS system needs some form of augmentation to increase the availability. If some form of augmentation is required the recommendation is to study the implications of integrating a barometric altimeter with the GPS equipment.

There are several implications for using the barometric altimeter for navigation. Currently it is used by the pilot as an independent determination of the height during CAT I approach. If it is used as is suggested above, the height source is no longer independent from the vertical guidance system. These problems include static defect, mechanical problems, calibration errors, and others. Besides these problems, the performance of the altimeter when local weather is rapidly changing needs to be assessed, and operational or technical procedures need to be developed to provide the user with calibration values during the terminal and approach phases of flight.

If problems with the barometric altimeter are unresolvable, the two augmentations that have the most promise are clock coasting and adding more transponders to geostationary satellites. Both are technical risks since it is not clear that the augmentations will satisfy the availability concern. Additional SVs for the GPS constellation is the only certain method to improve availability but it is an economic risk because of its cost.

In any case, a procedural solution to consider is to raise the decision height if the vertical accuracy is degraded.

SECTION 5

WDGPS ARCHITECTURE RECOMMENDATIONS

5.1 COMMON ELEMENTS

Based on the recommendations made in section 4, two architecture end-states were developed to provide near CAT I accuracies. Both end-states will contain at least two WMSs and ground earth stations (GESs), broadcast satellites, a number of WRSs, and ground network communications, as illustrated in figure 5-1.

The WRSs would be distributed throughout the US. They would be connected by way of the ground network communications lines to both WMSs in a "dual star" type network for redundancy. The WMSs would be either collocated with or located near the satellite uplink stations. The differential corrections calculated by the WMSs would be transmitted to the GESs. The GESs will transmit the message for satellite broadcast to users.

5.2 END-STATE ARCHITECTURES

In this section, two alternative end-state architectures are developed. Architecture 1 requires that the user equipment is capable of measuring the ionosphere (e.g. dual-frequency). A ground network of 10 reference stations would be adequate to provide the user with clock and ephemeris corrections in this instance. Such a network could be built around the five U.S. WIB monitor locations proposed by RTCA (formerly the Radio Technical Commission for Aeronautics). The analysis supporting the proposed sites may be found in [18]. Additional WRSs at ARTCC locations may be necessary to provide redundancy.

An example of such an architecture is shown in figure 5-2 and includes WRSs:

- At FAA facilities near the 5 proposed U.S. WIB monitor locations - Anchorage ARTCC, Honolulu ARTCC, Miami ARTCC, Bangor International Airport (near Halifax), and Los Angeles ARTCC.

- At 5 additional ARTCCs - Seattle, Denver, Chicago, Washington, D.C. and Houston.

The WMSs in this example are collocated with the ARTCC WRSs at Los Angeles and Washington, D.C. The ESs are Inmarsat uplink facilities.

Architecture 2 is for a ground network which is capable of providing sufficient ionospheric data to the user to support near CAT I accuracies. For this capability, around 20 WRSs would be required [12]. Again, the ground network could be built around the proposed WIB

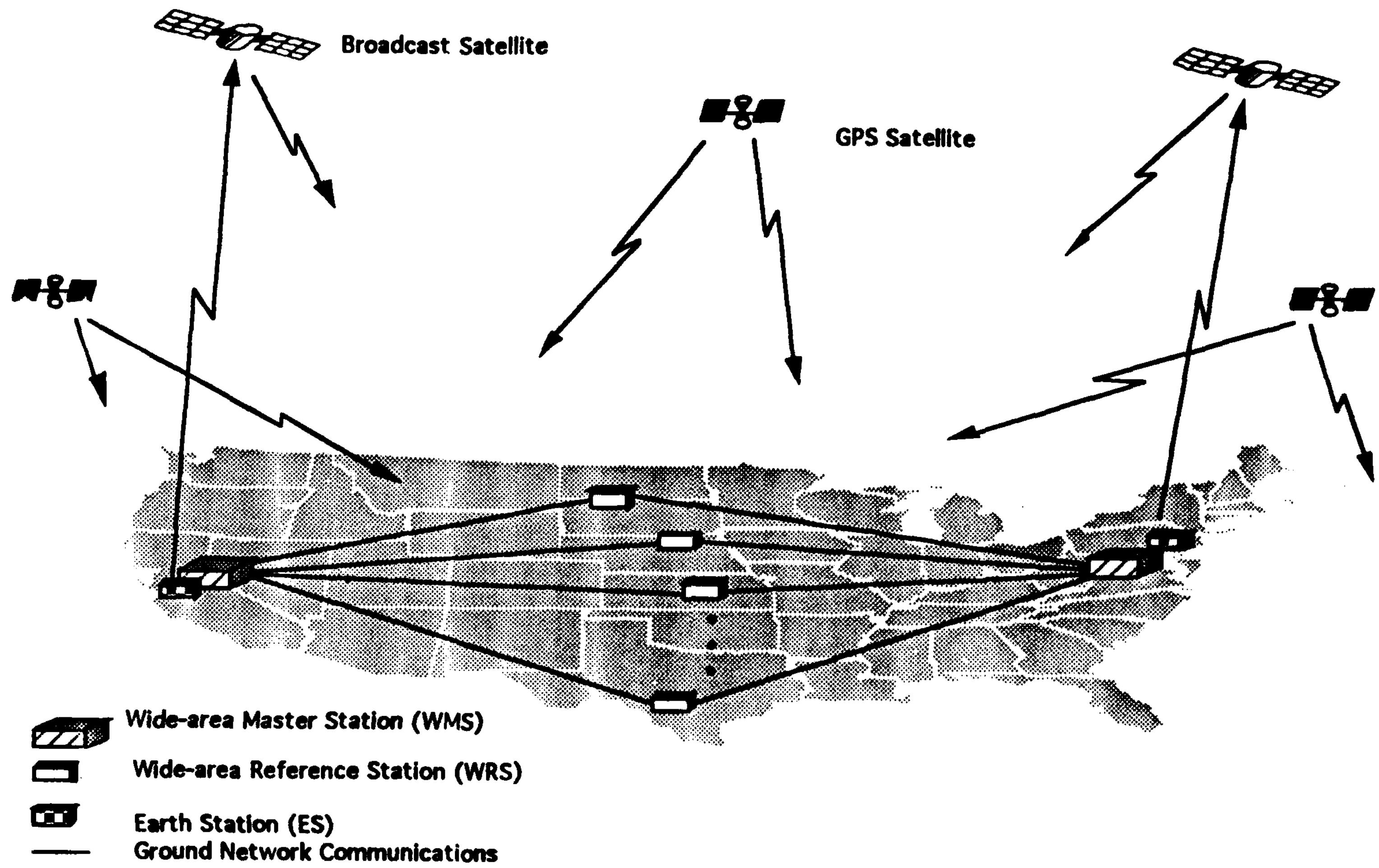

Figure 5-1. Common Elements of WDGPS Architecture

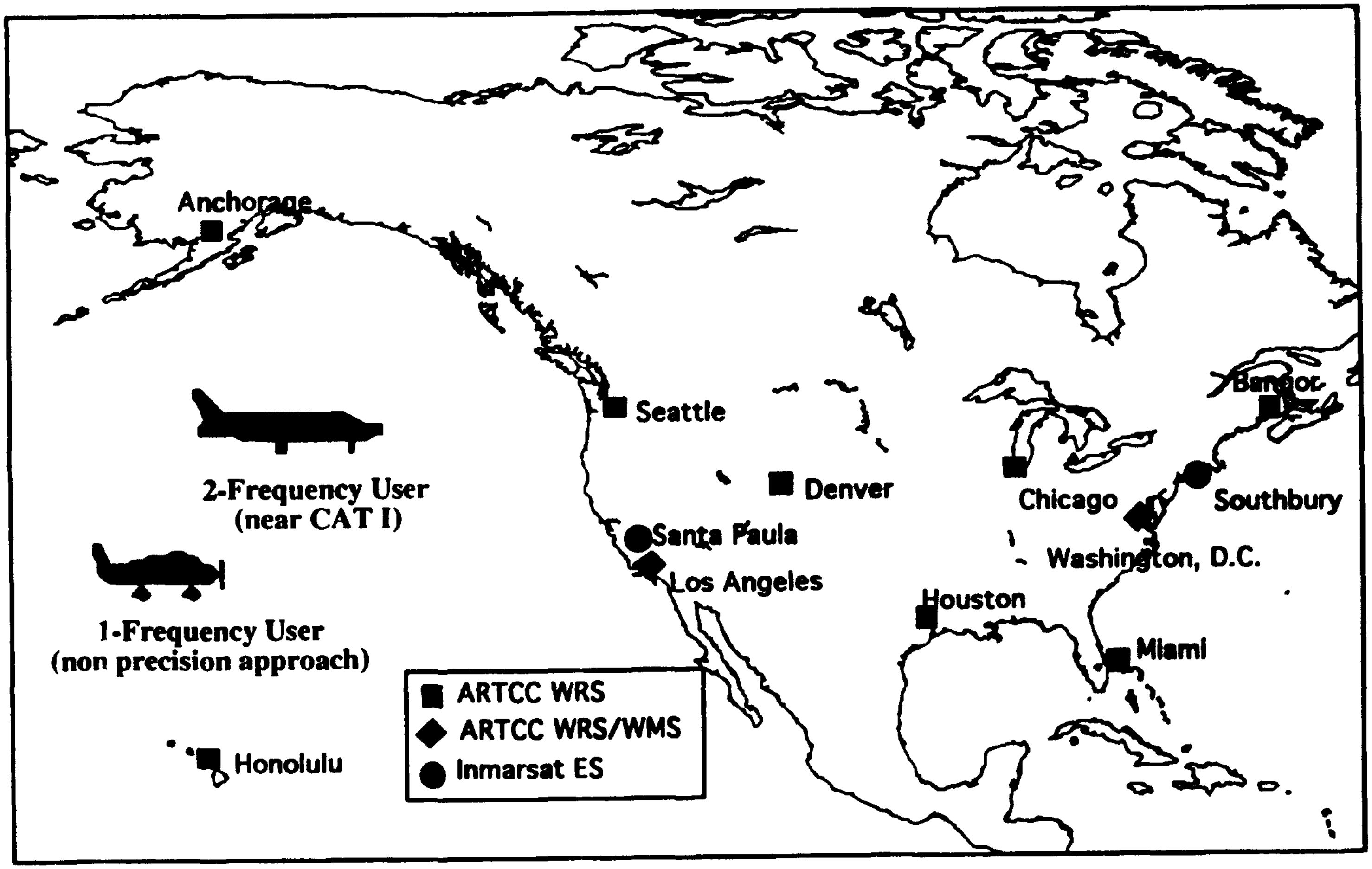

Figure 5-2. Architecture 1

monitor locations with the additional WRSs being located mainly at FAA ARTCC facilities.

Figure 5-3 depicts an example of Architecture 2: This example is an extension of the example of Architecture 1. Ten additional WRSs are added to obtain ionospheric delay coverage over CONUS. Nine of these are located at ARTCCs: Atlanta, Boston, Kansas City, Minneapolis, Salt Lake City, Albuquerque, Jacksonville, Cleveland and Oakland. The remaining WRS is at an international airport: Glasgow International in Montana.

5.3 GROUND NETWORK EVOLUTION

A three step process is envisioned for the ground network evolution:

(1) Implementation of WIB Network - The first step is to implement the planned WIB network. Around 10 WRSs will be installed (5 RTCA locations + 5 additional FAA facilities for redundancy). The network will be used only to provide integrity to users for NAS operations through non precision approaches. To facilitate the transition to WDGPS, it is recommended that a compatible message format be adopted at this stage. Data collection from the WIB monitors as well as the operational experience gained from the first step should prove useful for the transition to later steps.

(2) WDGPS with coarse ionospheric data - The data from the same set of WRSs will be processed to separate the clock and ephemeris corrections. The amount of ionospheric data will be insufficient to provide near-CAT I accuracies for single-frequency users, but dual-frequency users will have this capability.

(3) Select end state - At this stage, the end-state architecture is selected. If architecture 1 is decided, then the ground network will be complete as it is, but user equipment for estimating ionospheric delays will have to be standardized. If architecture 2 is decided, then the network will be expanded to 20 WRSs to provide sufficient ionospheric ground measurements to provide near-CAT I accuracy to all users. Dual-frequency users may be provided with lower decision heights because of the better accuracy of their ionospheric delay estimates.

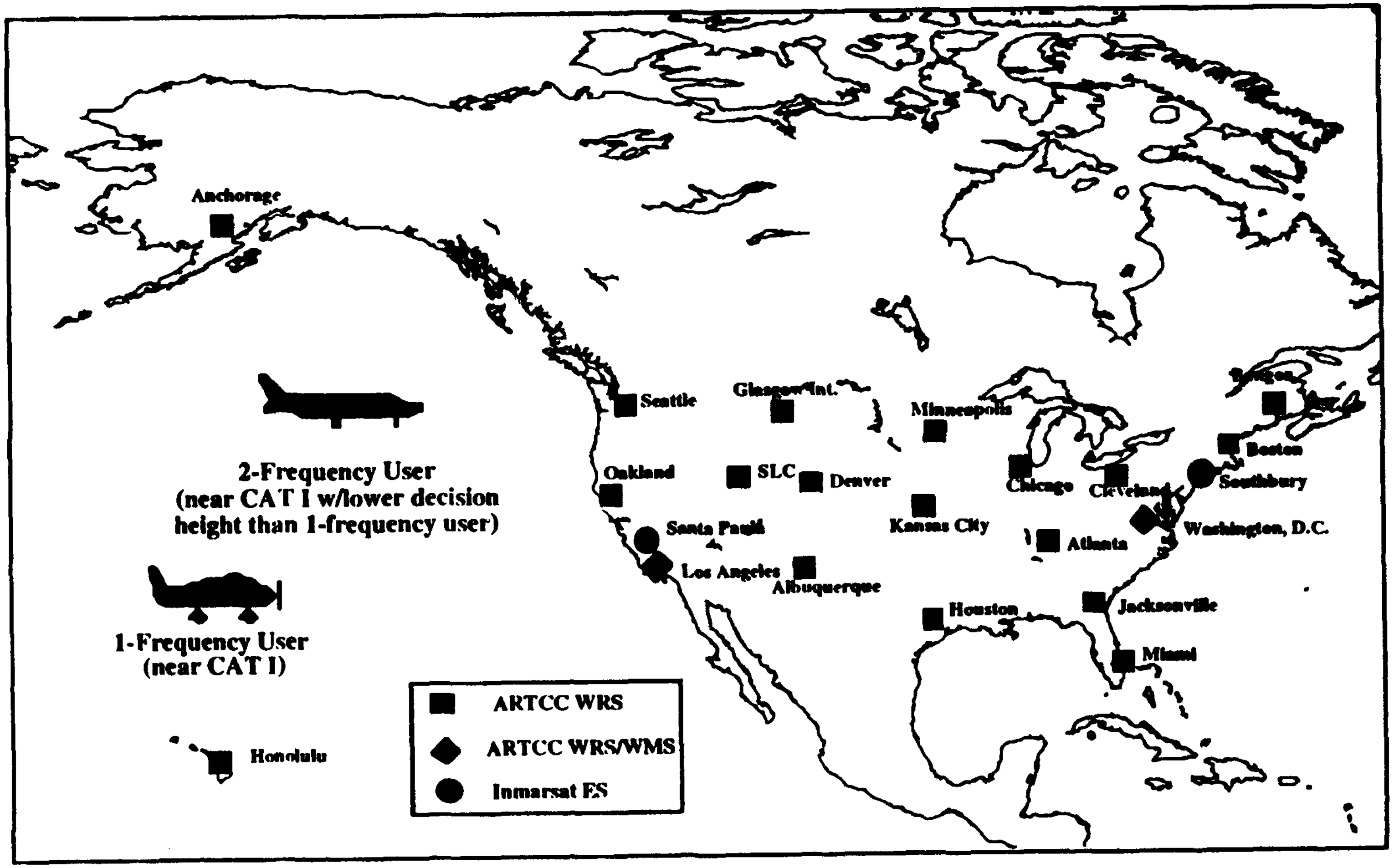

Figure 5-3. Architecture 2

5.4 MESSAGE STRUCTURE

To ensure a smooth transition from WIB to WDGPS, it is desirable to use a message structure which has separate slots for clock, ephemeris and ionospheric corrections right from the beginning. Initially, the clock and ephemeris corrections can be added together and placed in the clock slot [5]. This concept is illustrated in figure 5-4. The lumping together of the two error components may be necessary as the WRSs are installed since during this period there may not be a sufficient number of stations to accurately separate these components. Additionally, the suboptimal accuracy provided by lumping together the clock and ephemeris corrections will be entirely sufficient since the only objective of the initial implementation is to provide integrity for operations down through non-precision approaches.

	CLOCK/CLOCK RATE SLOT	EPHEMERIS SLOT	IONOSPHERE SLOT
IMPLEMENTATION FOR WIB:	Lumped Clock and ephemeris	0000	Coarse Iono.
IMPLEMENTATION FOR WDGPS:	Clock and clock rate	Ephemeris	Coarse or precise iono.

Figure 5-4. WDGPS/WIB Message Structure

SECTION 6

SUMMARY OF RECOMMENDATIONS

Figure 6-1 is a decision diagram which provides a summary of all of recommendations made in sections 3 and 4 of this report.

Beginning on the left, at alternative concepts, the recommendation to use WDGPS was made. This recommendation was based on the fact that the other alternatives did not have the coverage (in the case of long-range DGPS services) or did not have the performance (in the case of undiluted GPS) to achieve near CAT I precision approach landings at a large number of runways.

From this decision, and proceeding to the right in the diagram, the study recommended for broadcast media the geostationary SV with ranging option. Options for the WDGPS correction technique were studied. At this decision point a single recommendation could not be made, and two branches were taken. They were: 1) to use "fully separate" differential corrections with a separate ionospheric correction, and 2) to use fully separate differential corrections without any ionospheric correction. The second option was based on receiver technology which is evolving that may allow users to estimate ionospheric delay using dual frequency receivers or codeless L1/L2 receiver technique.

In the decision for the type of reference station to use, the recommendation was WRSs located at FAA facilities. These additional WRSs would only be required if the previous decision on WDGPS correction technique is to provide an ionospheric correction*. For network interconnections, the recommendation was to use FAA interfacility communications links (e.g., LINCS or RCL). Finally, if augmentations are required to achieve availability, the recommendation was made to consider supplementing vertical guidance with barometric altimeter input or additional geostationary transponders.

Section 5 developed two alternative end-state architectures based on the options of providing the ionospheric delay corrections from either the broadcast message of ground-based measurements or airborne-derived measurements. The first was developed under the assumption that future receivers would be able to directly measure the ionosphere using codeless technology on L2. The second architecture assumed a class of users that would prefer a lower cost single-frequency receiver over the better performance. Since the second architecture is simply an extension of the first, an evolutionary implementation was identified in which no immediate decision is required on which will ultimately be selected. Future technology may make the two frequency receiver cost effective for all classes of users.

* Preliminary WDGPS ground network reliability analyses indicate that some additional WRSs may be needed regardless to provide sufficient system integrity.

Finally, it was recommended that a WDGPS message format be adopted for initial WIB service to simplify the transition from WIB to WDGPS.

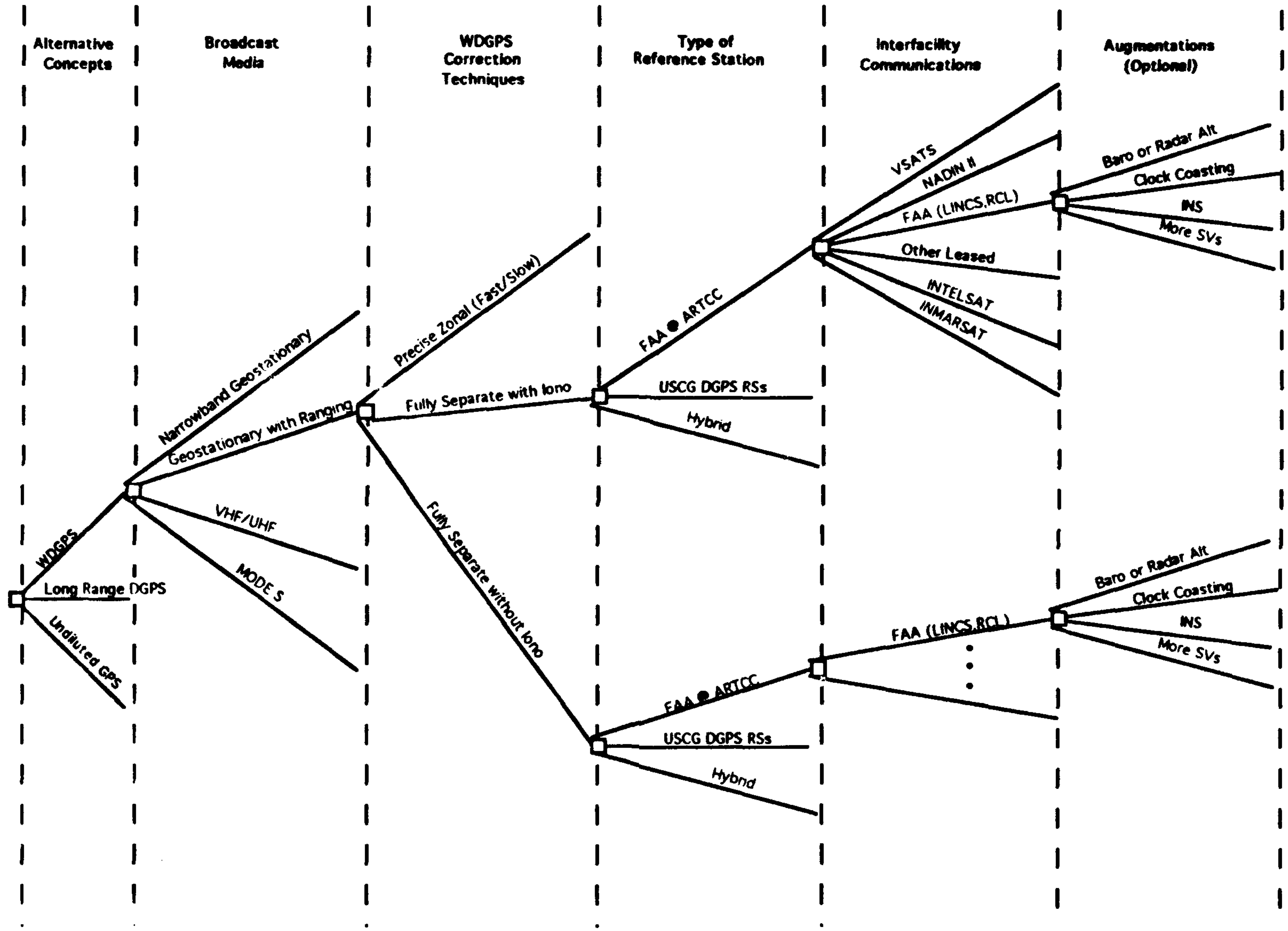

Figure 6-1. Summary of WDGPS Recommendations

SECTION 7

RISK ISSUES

7.1 OVERVIEW

This section presents the risk issues that were identified in this study. The issues have been categorized as either technical or economic risks. Some of the issues need to be resolved early in the program. They are identified in section 7.2. Other issues do not need to be resolved until later in the program, after the initial implementation has been completed. They are identified in section 7.3. Availability and other risks are identified in sections 7.4 and 7.5 respectively.

7.2 INITIAL IMPLEMENTATION

For the initial implementation, a technical and economic risk area is the identification and selection of a broadcast satellite provider(s). This selection must take into account coverage, redundancy, cost, and schedule.

7.3 SELECTION OF END-STATE

After the initial implementation has been completed, a decision has to be made concerning the selection of the desired end-state architecture. To make this decision, a number of risk areas need to be resolved, and a comparison made between the remaining risk in implementing architecture 1 and that in implementing architecture 2.

For architecture 1, a technical risk is the feasibility and performance of the ionospheric estimation by codeless L1/L2 receivers, and an economic risk is the cost to the user for such a receiver. With this architecture additional WRSs are not expected to be required. For the second architecture an economic risk is the cost of the additional WRSs, and the performance of the ground based ionospheric corrections.

7.4 AVAILABILITY

Even with a selected end-state architecture, there is a risk that the system will not be suitable for sole-means navigation, and will only be suitable for supplemental navigation. This risk is due to the fact that it is not known whether the selected architecture will have the required level of availability for sole-means.

To reduce this risk, an availability study needs to be performed for the selected architecture without any augmentation. If the availability is found to be unacceptable for sole-means, then some form of augmentation would be required. Since the barometric altimeter was the recommended augmentation, a technical and economic risk area concerns the performance and cost of improvements to the barometric altimeter. If the barometric altimeter option is

found to be unacceptable, then the recommended augmentation may be to add additional geostationary transponders, additional SVs, and clock coasting. In this case there is an economic risk concerning the cost of the additional space vehicles and the cost of improving the receiver clock and the cost of implementing clock coasting. For geostationary transponders, the institutional risks are finding the additional satellite providers, and developing leasing agreements. For additional SVs, there may also need to be some form of agreement between the FAA and the DoD concerning possible use of the Consolidated Space Operations Center (CSOC) for management and control of the additional satellites.

7.5 OTHER

Finally, this study also identified the following two other risk areas. These risks are common to both the initial implementation and the selected end-state architecture. The first risk is the effect of processing and message format delays on integrity response time.

The second risk is the effect of radio frequency interference due to either intentional or unintentional interference of user or ground GPS receivers and the WDGPS satellite broadcast signal. According to [19], it may be possible to spoof the WDGPS signal with a powerful C-band transmitter. The vulnerability of the system to such an attack is currently under debate.

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GLOSSARY

ACRONYMS

ARTCC	Air Route Traffic Control Center
CAT I	Category I
CONUS	Conterminous United States
CSOC	Consolidated Space Operations Center
DoD	Department of Defense
DGPS	Differential GPS
DSCS	Defense System Communications Satellite
FAA	Federal Aviation Administration
FAATSAT	FAA Telecommunications Satellite
GA	General Aviation
GES	Ground Earth Station
GLONASS	Global Navigation Satellite System
GPS	Global Positioning System
ILS	Instrument Landing System
IRS	Inertial Reference System
LADGPS	Local-area Differential GPS
LINCS	Leased Interfacility NAS Communications System
LOS	Line of Sight
NAS	National Airspace System
NDB	Nondirectional Beacon
PRN	Pseudo Random Noise
RAIM	Receiver Autonomous Integrity Monitor
RCL	Radio Communications Link
RCR	Routing and Circuit Restoral

SA	Selective Availability
SV	Space Vehicle
TSARC	Transportation System Acquisition Review Council
UHF	Ultra High Frequency
USCG	United States Coast Guard
VDOP	Vertical Dilution of Precision
VHF	Very High Frequency
VOR	VHF Omnidirectional Range
VSAT	Very Small Aperture Terminal
WARC	World Administrative Radio Conference
WADGPS	Wide-area Differential GPS
WDGPS	Wide-area Differential GPS
WIB	Wide-area Integrity Broadcast
WMS	Wide-area Master Station
WRS	Wide-area Reference Station